An Operational Technology for Assimilating Lagrangian Data Based on Dynamical Systems Techniques

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Award #: N00014-04-1-0191
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LONG-TERM GOAL

Much data in the ocean is Lagrangian in nature. Its full use in ocean prediction could advance significantly the Navy's ability both to predict ocean conditions and to assess the optimal strategies for deploying Lagrangian observational devices and their associated sensors. The development of a fully operational, integrated data assimilation scheme will afford such a naval predictive capacity in fixed ocean regions that can be comprehensively surveyed by Lagrangian measuring devices. The long-term objective of this project is the building of comprehensive and reliable data assimilation (DA) platform for incorporating Lagrangian data into ocean models. It will form the basis of an integrated prediction scheme for the ocean that can feed on both purely Lagrangian and mixed source data.

OBJECTIVES

This project aims to develop an operational technology for assimilating Lagrangian data. This new LaDA platform is expected to be particularly effective in ocean regions where coherent structures such as ocean eddies dominate the circulation. Focuses are put on: 1) extension of our Lagrangian data assimilation (LaDA) approach to develop a flexible platform, in which a variety of moving instruments that may not be viewed as Lagrangian in a conventional sense can be integrated; 2) design of observing systems to take full advantages of any moving instruments; 3) formulation of automated algorithms for optimal deployment strategies of the moving instruments to maximize the information content as observation and enhance predictive skill of the DA system; and 4) incorporation of dynamical systems theory to enhance predictive skill, in particular coherent structures and tracer fields associated with them.

We use the term “Lagrangian data” in the broadest sense, including the positions of various moving instruments along the trajectories as well as time sequence of the tracer fields. Autonomous vehicles (AVs) that glide or maneuver in the ocean are new types of moving instruments that will be incorporated into our extended LaDA platform as a part of the control variables. AVs have come to be a stable and reliable mean to measure water properties. The platform will be ideal for designing and performing the autonomous ocean sampling network, adaptive observations, and optimal deployment plans of such moving instruments. The extension will also have a capability to handle high-dimensionality and nonlinearity of the operational ocean models. An example of the structure of the tracer fields is an ocean color obtained by the satellites.

Report Documentation Page

Form Approved
OMB No. 0704-0188

Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.

1. REPORT DATE **30 SEP 2006**	2. REPORT TYPE	3. DATES COVERED **00-00-2006 to 00-00-2006**

4. TITLE AND SUBTITLE **An Operational Technology for Assimilating Lagrangian Data Based on Dynamical Systems Techniques**	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **University of California Los Angeles (UCLA),Department of Atmospheric and Oceanic Sciences &,Institute of Geophysics and Planetary,Los Angeles,CA,90095-1567**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**7**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

A comprehensive LaDA platform will be built upon balanced integration of data assimilation techniques and dynamical systems concepts. Recent developments in the theory and use of dynamical systems concepts for Lagrangian analysis will add a new dimension to the LaDA platform. Incorporating the geometrical approach will offer a much needed template for observing system design for the LaDA platform. In return, accurate estimation and forecast of Eulerian flow field by assimilating such data will strengthen further the reliability of the observing system with moving instruments.

APPROACH

Our approach is to use the LaDA as a basis for the development of an operational technology that accommodates assimilation of data from a variety of measurements by any types of moving instruments including drifters, floats, and AVs. Such a platform will be developed through a hierarchy of models and methods. Fundamental issues will be addressed using the idealized model flows. Basic tests will be performed on intermediate model flows, the double-gyre, shallow-water model with various wind forcings, and progressing to the realistic general circulation model for operational application in Gulf of Mexico. We will investigate to what extent the Lagrangian data can be used to estimate the three-dimensional flow evolution. We will improve the LaDA method to better deal with the chaotic nature of the Lagrangian dynamics. We address the localization and inflation issues that will help simplify estimates of error covariance and develop a Lagrangian Ensemble Kalman Filter (EnKF). Ideas from dynamical systems theory will be employed in every stage to provide a solid, mathematical template and foundation while casting conceptual simplicity on the complex platform. This project is a joint project by the two co-PIs, K. Ide (UCLA) and C.K.R.T. Jones (UNC-CH). G. Verineres is a postdoctoral fellow who works on the LaDA for Gulf of Mexico. H. Salman is a postdoctoral fellow who works on the applications of the dynamical systems theory to the LaDA. Liyan Liu is a graduate student who researches the vertical propagation of the information by the LaDA.

WORK COMPLETED

The progress is being made to push the Lagrangian data assimilation towards the operational use for the optimal deployment strategies.

Issues essential to the LaDA have been investigated further. In particular, due to the very nature of the Lagrangian data – chaotic dynamics due to the distinguished hyperbolic trajectories that govern the flow template and make the neighborhood tracers separate at an exponential rate - can lead to a filter divergence. A sophisticated quality-control method is being developed by combining the dynamical systems theory and the expectation-maximization algorithm.

To investigate the potential of surface drifter data in estimating the three-dimensional ocean flow, the LaDA is applied to the two-layer point vortex model. Vertical propagation of the observed information is examined in the light of the parameter estimation.

Towards the development an operational strategy, the optimal drifter deployment is investigated further using EnKF-based LaDA and the flow template regulated by the invariant manifolds. Currently the scheme is applied to a single-layer shallow-water ocean model.

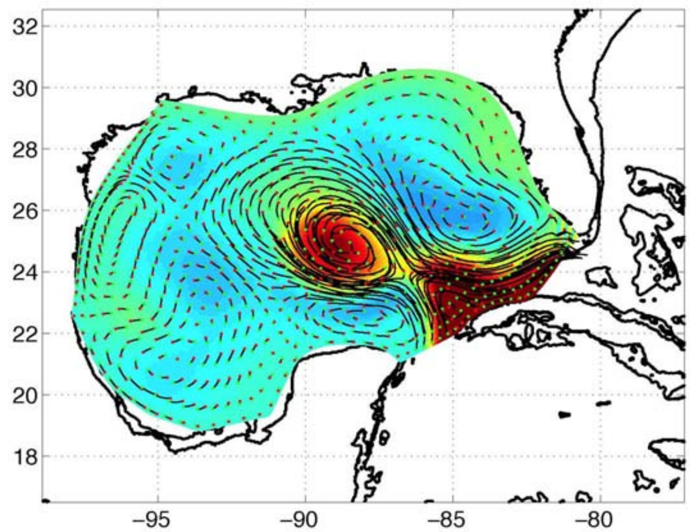

Figure 1. Surface Lagrangian and Eulerian fields of the Gulf of Mexico by the multi-layer reduced gravity model [Colors represent the sea surface height (Eulerian field). The black lines are 625 drifter trajectories over eight days(Lagrangian field). The green and red dots represent the departure and arrival points, respectively.]

A multi-layer reduced gravity model of the GOM is implemented. This modeling setup has been shown to be the simplest representation of the GOM that simulates the shedding of eddies. It is a first step toward a detailed representation of the physics of the GOM. The horizontal discretization uses a curvilinear grid. It has a horizontal resolution of about 5 km in the region of the loop current. The inflow and outflow conditions are the cosine shaped current at the Yucatan channel and the strait of Florida with respective width of 160 km and 150 km. In order to conserve the total mass in the Gulf, the inflow transport matches the outflow transport. This configuration allows us to reduce the number of degrees of freedom to a minimum without sacrificing on the resolution near the region of interest. The structured curvilinear grid of the horizontal discrete domain was created using elliptic grid generation techniques. The boundary of the grid, illustrated in Figure 1, follows the coastline.

For the assimilation of the tracer field, we have added a functionality to compute the passive racer field as represented in Figure 2.

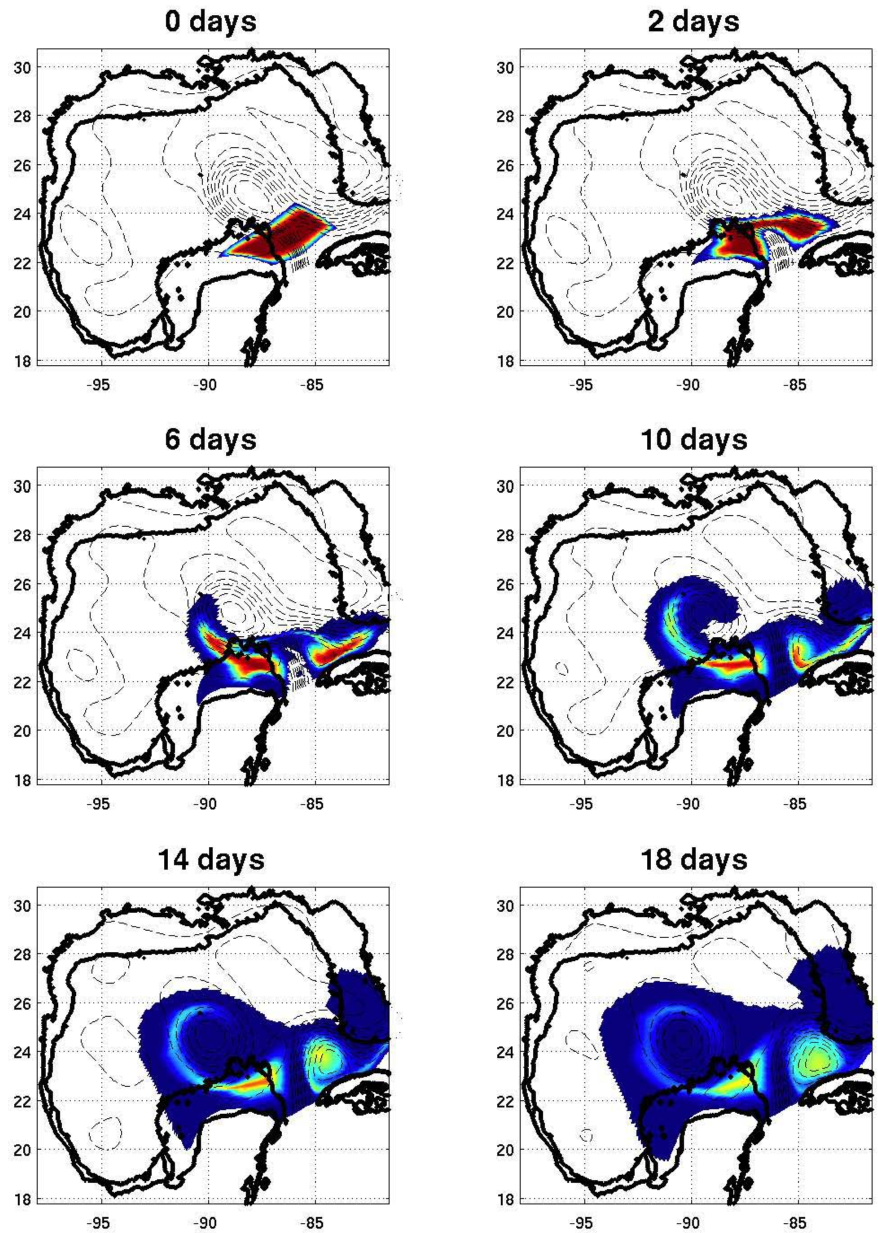

Figure 2. Lagrangian tracer fields of the Gulf of Mexico by the multi-layer reduced gravity model [Colors represent the normalized concentration of the tracer. The dashed black lines represent the sea surface height.]

RESULTS

By combining the EM-algorithm, the tracer control scheme can detect the hyperbolic effect more reliably and may lead to a robust LaDA method.

The LaDA method can successfully estimate the highly-idealized multi-layer point vortex model within the Rossby radius of deformation. The barotropic mode plays a key role as expected.

For the multi-layer model configuration of Gulf of Mexico, the current is confined to the 2 upper most layers with the ratio of transports between the two upper layers being kept constant. The upper most layer carries 80 % of the total volume transport.

For the development of theoretical deployment strategies, the problem is made complicated by the fact that the positions of Lagrangian data are continuously changing with time by the underlying flow field. In order to tackle this problem, an understanding of how the underlying flow field governs the motion of Lagrangian data is required. This problem is most naturally addressed using recent ideas borrowed from dynamical systems theory to extract Lagrangian coherent structures. These structures have been studied extensively for geophysical flows in recent years and are understood to orchestrate the evolution and notion of material particles.

Figure 3a illustrates the locations of several key structures that were identified for our double gyre flow experiments. Also shown are the deployment sites of sets of drifters in relation to these various structures. Figure 3b illustrates the convergence of the data assimilation method for several different sites. For reference purposes, a case with no data assimilation is included. The figure compares four different cases; uniformly released drifters, drifters released at saddle trajectories, drifters released within coherent vortices, and finally a combination of saddles and centers. In all the cases considered, nine drifters were used for the data assimilation. The results clearly show that the uniform launch produces the optimum convergence although at the expense of having to release the drifters in regions remote from one another. In stark contrast, targeting Lagrangian saddle points appears to produce equally accurate results at long times but with only three different release sites for the nine drifters. This occurs because Lagrangian saddle points can disperse drifters over a wide region providing effective sampling of the entire flow field. Therefore, by exploiting the internal dynamics of the governing flow field through the targeting of Lagrangian coherent structures, we are able to optimize the performance of our method through the optimal deployment of drifters.

The LaDA-EnKF works effectively for ocean data assimilation using a shallow-water model (Figure 2) by applying the localization radius. An advantage of this method over other existing methods is that the assimilation time interval can be as long as the Lagrangian correlation time scale.

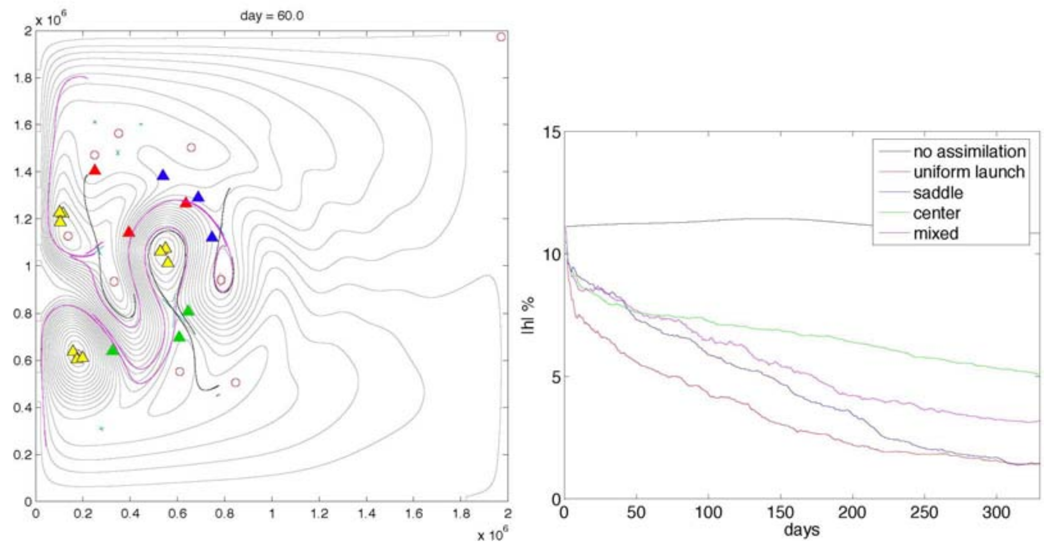

Figure 3. Results for directed drifter deployment strategy. [a) Lagrangian coherent structures superimposed on the height field at day 60. B) Error in the height field.]

Judicious computation of the error correlation and innovative construction method for error correlation are crucial in the coastal data assimilation system using the variational approach.

IMPACT/APPLICATION

Observation of the chaotic dynamical system can be assimilated effectively as the quality control scheme.

The LaDA-EnKF will enable us to assimilate drifter data into realistic ocean model.

The flow-template approach shows a promising potential to the effective design of the optimal drifter deployment strategies.

RELATED PROJECTS

1– NSF CMG Heavy Tailed Distributions in Geophysical flow: Physical Mechanisms and Data Assimilation, in collaboration with Richard McLaughlin, Roberto Camassa and Christopher K.R.T. Jones (UNC-CH) and Didier Sornette (UCLA).

2– Los Alamos National Laboratory project on data assimilation studies for shock wave physics in collaboration with Jim Kao (Los Alamos National Laboratory).

PUBLICATIONS

Chin, T.M., K. Ide, C.K.R.T. Jones, L. Kuznetsov and A.J. Mariano, 2006: Mapping, Assimilation, and Optimization Schemes, in Dynamic Consistency and Lagrangian Data in Oceanography: Analysis and Prediction of Coastal and Ocean Dynamics, Cambridge University Press, Accepted

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